

## APPENDIX B

### VAPOR PHASE CARBON DESIGN EXAMPLES

**B-1. Example 1—SI Units.** This example will illustrate the design calculations for sizing a vapor phase activated carbon treatment unit. The treatment train for this example consists of a blower, an air stripper, a heat exchanger, and carbon vessels to treat air from the air stripper containing the following volatile organic chemicals (VOC): perchloroethylene (PCE), trichloroethylene (TCE), benzene, and toluene (see Figure B-1). The water containing the VOCs enters the top of the air stripper column and flows generally downward through the packing material. At the same time, air flows upward through the column (countercurrent flow). As water and air contact, the VOCs are transferred from the water phase to the air phase. The water leaves the bottom of the column depleted in VOCs. The VOCs that have been transferred to the air exit the top of the column in the air phase. This air phase then flows through a heat exchanger where it is heated from 289 to 300 K to lower the relative humidity from 100 to 50%. From here, the air phase flows through vessels filled with activated carbon. The activated carbon adsorbs the VOCs. The air phase, depleted of VOCs, is discharged to the atmosphere.

*a. Parameters.*

- Flow rate of the air phase entering the air blower:  $1 \text{ m}^3/\text{s}$ .
- Temperature of the vapor stream into the blower: 305 K.
- Run time between carbon changes: 3 months/vessel.
- Number of carbon vessels: two (in series).
- Atmospheric pressure 87.6 kPa (elevation of site approximately 1600 m above sea level).
- Temperature of air phase leaving the air stripper: 289 K.
- Contaminants and their concentrations leaving the air stripper in the air phase:
  - o Perchloroethylene (PCE): 15 ppmv.
  - o Trichloroethylene (TCE): 14 ppmv
  - o Benzene: 9 ppmv.
  - o Toluene: 5 ppmv.

*b. Design Steps.*

- (1) Determine the amount of carbon needed for 3 months.
- (2) Determine the size of the carbon adsorption vessels.
- (3) Determine the total pressure drop through the treatment train:
  - (a) Air stripper and associated piping, valves, and instrumentation.
  - (b) Air stripper to heat exchanger piping, valves, and instrumentation.
  - (c) Heat exchanger.
  - (d) Heat exchanger to carbon vessels piping, valves, and instruments.
  - (e) Carbon vessels.
  - (f) Piping between carbon vessels.
  - (g) Carbon vessel to ambient air discharge point.
- (4) Determine the type and size of the blower.
- (5) Determine the type and size of the heat exchanger.

*c. Detailed calculations.*

(1) *Determine the amount of carbon needed for 3 months.* For this example, initially assume that two carbon vessels in series will be used. The air phase from the air stripper will flow through the first vessel (the lead vessel) that adsorbs most of the organic vapors. The air phase will then flow through the second vessel (lag vessel) and be discharged to the atmosphere. After the effluent concentration equals the influent concentration, the flow will be redirected first through the lag vessel. This assumes that the second vessel contains the same amount of carbon as the first vessel. The lag vessel now becomes the lead vessel. The other vessel will have the exhausted carbon regenerated or replaced and put back on-line as the lag vessel. The length of time that a carbon vessel should remain on-line is very site-specific. In this example, design the system for 3 months between carbon changes of the lead vessel. It is difficult to determine the exact amount of carbon needed. Below is a method of estimating the amount of activated carbon that is needed.

(a) *Calculate the Partial Pressure of Each Contaminant in the Vapor Stream.* Assume that the pressure in the carbon vessel is the same as the discharge pressure (87.6 kPa). If this pressure is too different from the actual pressure, the partial pressure will need to be recalculated for the correct pressure in the carbon vessels. The weight of contaminant that can be adsorbed per weight of activated carbon can be estimated from isothermal data supplied by the carbon manufacturer or from the literature (see Paragraph 3-3a). From these data, the weight of contaminant adsorbed per weight of carbon was estimated from the Freundlich isotherm relationship:

$$\frac{x}{m} = KC \left( \frac{1}{n} \right) .$$

The values of  $K$  and  $(1/n)$  were obtained for one carbon type at 298 K. These values must be obtained for each type of carbon being evaluated and for each temperature (see Table B-1).

**Table B-1**  
**Freundlich isothermal data**

| Contaminant | Temp. | $K$   | $C$ (kPa)             | $1/n$ | $x/m$ |
|-------------|-------|-------|-----------------------|-------|-------|
| PCE         | 298 K | 1.0   | $1.3 \times 10^{-3}$  | 0.144 | 0.384 |
| TCE         | 298 K | 0.95  | $1.2 \times 10^{-3}$  | 0.263 | 0.162 |
| Benzene     | 298 K | 0.388 | $0.79 \times 10^{-3}$ | 0.131 | 0.152 |
| Toluene     | 298 K | 0.565 | $0.44 \times 10^{-4}$ | 0.111 | 0.240 |

See appendix C for generation of isotherms. See Paragraph 2-3 for a discussion of  $K$  and  $1/n$ .

(b) *Determine the Weight of Each Contaminant to be Adsorbed Per Unit Time.*

$$\frac{\text{g mole air}}{\text{min}} = n = \frac{PV}{RT} = \frac{\left( 87.6 \text{ kPa} \times \frac{1 \text{ m}^3 \times 60 \frac{\text{s}}{\text{min}}}{\text{s}} \right)}{\left( 8.31 \times 10^{-3} \frac{\text{m}^3 \text{ kPa}}{\text{g mole K}} \times 289 \text{ K} \right)}$$

$$= \frac{2.19 \times 10^3 \text{ g mole air}}{\text{min}} = \frac{2.19 \text{ kg mole air}}{\text{min}}$$

$$\frac{\text{kg mole PCE}}{\text{min}} = \frac{2.19 \text{ kg mole}}{\text{min}} \left( \frac{15 \text{ ppmv PCE}}{10^6 \text{ ppmv air}} \right)$$

$$= \frac{3.28 \times 10^{-5} \times \text{kg mole}}{\text{min}} \text{ PCE}$$

$$\frac{\text{kg PCE}}{\text{min}} = \left( \frac{\text{kg mole PCE}}{\text{min}} \right) (\text{molecular weight of PCE})$$

$$= \frac{3.28 \times 10^{-5} \text{ kg mole}}{\text{min}} \times \frac{166 \text{ kg}}{\text{g mole}} = \frac{5.44 \times 10^{-3} \text{ kg PCE}}{\text{min}}$$

$$\frac{\text{kg PCE}}{3 \text{ months}} = \left( \frac{\text{kg PCE}}{\text{min}} \right) \left( \frac{1440 \text{ min}}{\text{day}} \right) \left( \frac{30 \text{ day}}{\text{mo}} \right) 3 \text{ months}$$

$$= 5.44 \times \frac{10^{-3} \text{ kg}}{\text{min}} \times 1440 \times 30 \times 3 = \frac{706 \text{ kg PCE}}{3 \text{ months}}$$

$$\frac{\text{kg carbon}}{3 \text{ months}} = \left( \frac{706 \text{ kg PCE}}{3 \text{ months}} \right) \left( \frac{\text{g carbon}}{0.384 \text{ g PCE}} \right)$$

$$= \frac{1839 \text{ kg carbon}}{3 \text{ months}}$$

$$\text{kg carbon for } \frac{\text{TCE}}{3 \text{ months}} = 3213 \text{ kg}$$

$$\text{kg carbon for } \frac{\text{benzene}}{3 \text{ months}} = 1311 \text{ kg}$$

$$\text{kg carbon for } \frac{\text{toluene}}{3 \text{ months}} = 507 \text{ kg}$$

$$\text{Total lb carbon for 3 months } (1839 + 3213 + 1311 + 507) = 6870 \text{ kg}$$

This calculation is only an estimate of the quantity of carbon required. Manufacturers recommend calculating the carbon needed for the three or four most prevalent constituents and then adding a safety factor. Safety factors may be as little as 20% more carbon than calculated for non-regenerable systems to as much as 100% for a very conservative design. Applying this to this example, we can see that the estimated carbon total  $M$  becomes:

$$(6870 \text{ kg}) (2) = (13740) \text{ kg for 3 months}$$

(2) *Determine the Size of the Carbon Adsorption Vessels.*

(a) *Estimate the Diameter of the Carbon Vessel.* The designer often has the option, within limits, of using a large diameter vessel that is short or a smaller diameter vessel that is tall. Both will hold the same amount of carbon. As a starting point, calculate the diameter for a reasonable superficial velocity. Superficial velocity ( $V$ ) is the velocity that the vapor would attain through the carbon bed that if this vessel were empty ( $V = Q/A$ , where  $Q$  is the vapor flow rate and  $A$  is the cross-sectional area of the vessel). Many carbons can be used over a large range of superficial velocities. Manufacturers' literature lists superficial velocities from 2.5 cm/s to several hundred. Typical superficial velocities are 5 to 50 cm/s. As superficial velocities increase, the pressure drop through the vessel increases. This results in increased energy costs. For this example, initially assume a superficial air velocity through the carbon vessels of 25 cm/s. Calculate the resulting diameter  $D$  of the vessel as follows:

$$A = \frac{Q}{V}$$

$$A = \left[ \frac{3.14}{4} \right] [D^2]$$

Combining yields:

$$D = \left[ \frac{4Q}{3.14V} \right]^{0.5} = \left[ \frac{4 \left( \frac{1 \text{ m}^3}{s} \right)}{(3.14) \left( \frac{25.4 \text{ cm}}{s} \times \frac{1 \text{ m}}{100 \text{ cm}} \right)} \right]^{0.5} = 2.24 \text{ m}$$

(b) *Estimate the depth of the carbon in the vessels.*

$$M = [Vol] [\text{carbon density}]$$

$$Vol = \left[ \left( \frac{3.14}{4} \right) \right] \left[ (D^2) (H) \right]$$

where

$Vol$  = volume of the carbon in the vessel

$M$  = weight of the carbon

$H$  = depth of the carbon in the vessel.

Combining, rearranging and estimating the carbon density to be  $489 \text{ kg/m}^3$  yields

$$\begin{aligned} H &= \frac{(4)(M)}{(3.14)(D^2)(\text{carbon density})} \\ &= \frac{(4)(13740 \text{ kg})}{(3.14) \left( (2.24 \text{ m})^2 \left( 489 \frac{\text{kg}}{\text{m}^3} \right) \right)} \\ &= 7.2 \text{ m} \end{aligned}$$

The carbon vessel is too deep. By decreasing the superficial velocity through the carbon bed from 25 to 12.5 cm/s and repeating the calculations done in Paragraphs B-1c(2)(a) and B-1c(2)(b) above, the diameter of the vessel becomes 3.2 m and the carbon depth becomes 3.6 m. These are acceptable (an alternative is to use four vessels  $2 \times 2$ ). Vessels available from manufacturers will dictate their exact height and diameter.

(3) *Calculate the Total Pressure Drops Through the Units in the Process Train.* The actual pressure drops must be calculated for each application. They will most likely differ much from those chosen here to illustrate the calculation procedure.

- (a) *Blower Through Air Stripper, Valves, and Instruments.* 13 cm H<sub>2</sub>O (estimate).
- (b) *Air Stripper to Heat Exchanger Piping, Valves, and Instruments.* 2.5 cm of H<sub>2</sub>O (estimate).
- (c) *Heat Exchanger.* 2.5 cm of H<sub>2</sub>O (estimate).
- (d) *Heat Exchanger to Carbon Vessels Piping, Valves, and Instruments.* 2.5 cm of H<sub>2</sub>O (estimate).
- (e) *Carbon Vessels.* The pressure drop through the carbon bed is a function of the type and size of carbon, the velocity of the vapor through the carbon bed, and the depth of the bed. For one specific carbon in manufacturers' literature, the pressure drop through the carbon is 6 cm H<sub>2</sub>O per meter of carbon. For the 3.6-m bed of carbon in this example, the pressure drop is 21 cm of H<sub>2</sub>O for the lead vessels and 21 cm of H<sub>2</sub>O for the lag vessel, for a total of 42 cm of H<sub>2</sub>O (see Figure B-1).
- (f) *Between Carbon Vessels.* 2.5 cm of H<sub>2</sub>O (estimate).
- (g) *Carbon Vessels to Ambient Air Discharge Point.* 2.5 cm of H<sub>2</sub>O (estimate).

(4) *Determine the Size and Type of Blower.*

(a) *Size of Blower.* Design the blower to handle 1 m<sup>3</sup>/s for the above total system pressure drop. The exit pressure from the blower is the pressure leaving the carbon units (87.6 kPa) plus the pressure drop through the treatment train. The blower exit pressure is as follows:

$$\begin{aligned}
 &= 87.6 \text{ kPa} + \left( (13 + 2.5 + 2.5 + 2.5 + 42 + 2.5 + 2.5) \text{ cm H}_2\text{O} \right) \frac{(9.8 \times 10^{-2} \text{ kPa})}{(\text{cm})} \\
 &= 94.2 \text{ kPa}
 \end{aligned}$$

Blower performance curves should be obtained from the manufacturer. In the absence of this information, the design engineer can estimate the power from thermodynamic relationships as

follows. (See an engineering thermodynamics book for an additional discussion and development of these relationships.)

$$P = [(P_1)(V_1)] \left[ \frac{k}{(k-1)} \right] \left[ \left( \frac{P_2}{P_1} \right)^{\frac{(k-1)}{k}} - 1 \right]$$

$P$  = Power, kW

$P_1$  = Inlet pressure in kPa = 87.6 kPa

$P_2$  = Outlet pressure in kPa = 94.2 kPa

$V_1$  = Inlet Volume =  $1 \frac{\text{m}^3}{\text{s}}$

$C_p$  = Heat capacity at constant pressure

$C_v$  = Heat capacity at constant pressure

$k$  = ratio of specific heats  $\frac{C_p}{C_v}$  ( $k = 1.4$  air; 1.31 methane; 1.3  $\text{CO}_2$ )

Substituting yields:

$$\begin{aligned} \text{Power} &= 87.6 \text{ kPa} \times \frac{1 \text{ m}^3}{\text{s}} \left[ \frac{(1.4)}{(1.4-1)} \right] \left[ \left( \frac{94.2}{87.6} \right)^{\left[ \frac{(1.4-1)}{1.4} \right]} - 1 \right] \\ &= 6.4 \text{ kW (at 100\% efficiency)} \end{aligned}$$

In the absence of manufacturers' data, estimate the efficiency of the blower and motor combination to be 40%. The actual size of the motor is then:

$$\text{Power} = \frac{6.4 \text{ kW}}{40\%} = 16 \text{ kW}$$

(b) *Type of Blower.* High-pressure centrifugal blowers are often used in this type of application.

(5) *Determine the Size and Type of Heat Exchanger.* The relative humidity (RH) of the vapor stream entering the carbon vessels should not exceed 40 to 70% (see Paragraph 3-1b). A heat exchanger is used to raise the temperature (lower the RH) or lower the temperature (raise the RH) as needed. High RH reduces the adsorption capacity of the carbon. High temperature reduces the capacity of the carbon. A good compromise between temperature and humidity is to raise or lower the RH to about 50%. The type of heat exchanger depends on the amount of

heating or cooling needed. Assume that in the air stripper the vapor stream is cooled to 289 K (the temperature of the water in the air stripper). Assume the vapor leaving the air stripper is saturated with moisture (100% RH). A psychrometric chart tells us that the temperature must be raised in a heat exchanger from 289 to 299.8 K to lower the RH to 50%.

- The Freundlich isothermal data listed in earlier are for 298 K. In this example, this is close to the 300 K vapor temperature of the vapor entering the carbon units. If the temperature difference is large, the weight of contaminant adsorbed per weight of carbon ( $x/m$ ) must be determined for the new temperature and all subsequent calculations repeated.
- In addition to increasing the pressure, the blower also raises the temperature of a vapor stream. If the vapor goes directly from the blower to the carbon units, the temperature may need to be reduced, not heated, in a heat exchanger. It is difficult to estimate the temperature rise. The temperature rise must be obtained from manufacturer's blower literature.

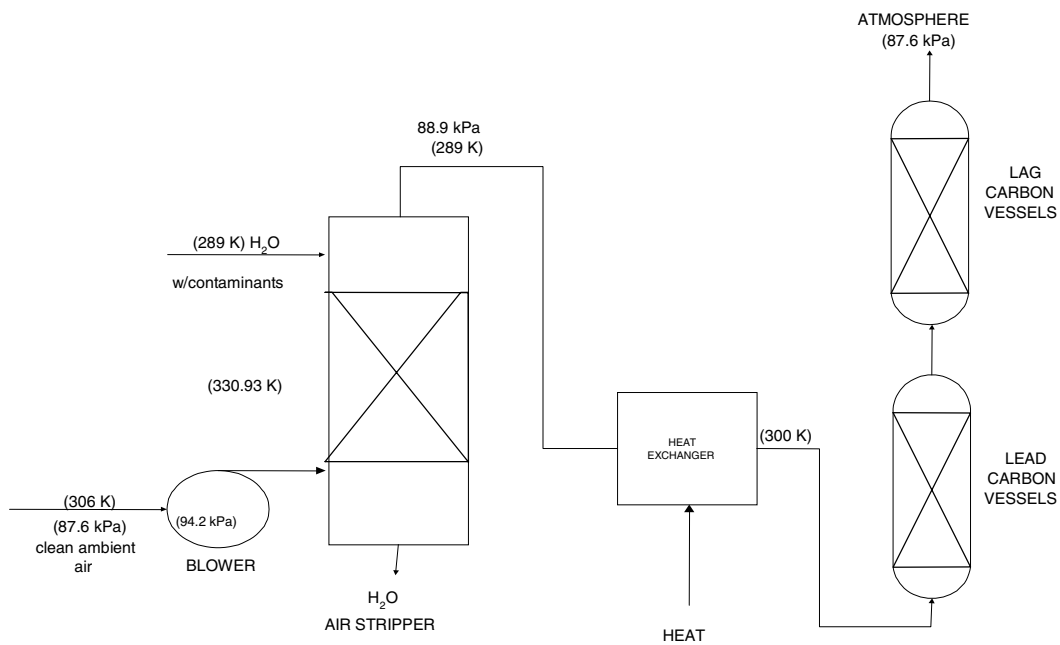


Figure B-1. Vapor phase activated carbon treatment train (SI units).

**B-2. Example 2—English units.** This example will illustrate the design calculations for sizing a vapor phase activated carbon treatment unit. The treatment train for this example consists of a blower, an air stripper, a heat exchanger, and carbon vessels to treat air from the air stripper containing the following volatile organic chemicals (VOC): perchloroethylene (PCE), trichloroethylene (TCE), Benzene, and toluene (see Figure B-2). The water containing the VOCs enters the top of the air stripper column and flows generally downward through the packing material. At the same time, air flows upward through the column (countercurrent flow). As water and air contact, the VOCs are transferred from the water phase to the air phase. The water leaves the bottom of the column depleted in VOCs. The VOCs that have been transferred to the air exit the top of the column in the air phase. This air phase then flows through a heat exchanger where it is heated from 60°F to 80°F to lower the relative humidity from 100 to 50%. From here, the air phase flows through vessels filled with activated carbon. The activated carbon adsorb the VOCs. The air phase, depleted of VOCs, is discharged to the atmosphere.

*a. Parameters.*

- Flow rate of the air phase leaving the air stripper: 2000 ft<sup>3</sup>/min.
- Temperature of the air phase into the blower: 90°F.
- Run time between carbon changes: 3 months/vessel.
- Number of carbon vessels: two (in series).
- Atmospheric pressure: 12.7 psia (elevation of site approximately 1 mile above sea level).
- Temperature of air phase leaving the air stripper: 60°F.
- Contaminants and their concentrations leaving the air stripper in the air phase:
  - o Perchloroethylene (PCE): 15 ppmv.
  - o Trichloroethylene (TCE): 14 ppmv.
  - o Benzene: 9 ppmv.
  - o Toluene: 5 ppmv.

*b. Design Steps.*

- (1) Determine the amount of carbon needed.

- (2) Determine the size of the carbon adsorption vessels.
- (3) Determine the total pressure drop through the process train.
  - (a) Air stripper and associated piping, valves, and instrumentation.
  - (b) Air stripper to heat exchanger piping, valves, and instrumentation.
  - (c) Heat exchanger.
  - (d) Heat exchanger to carbon vessels piping, valves, and instruments.
  - (e) Carbon vessels.
  - (f) Piping between carbon vessels.
  - (g) Carbon vessel to ambient air discharge point.
- (4) Determine the type and size of the blower.
- (5) Determine the type and size of the heat exchanger.

c. *Detailed Calculations.*

(1) *Determine the Amount of Carbon Needed.* For this example, initially assume that two carbon vessels in series will be used. The air phase from the air stripper will flow through the first vessel (the lead vessel) that adsorbs most of the organic vapors. The air phase will then flow through the second vessel (lag vessel) and be discharged to the atmosphere. After the effluent concentration equals the influent concentration, the flow will be redirected to flow first through the lag vessel. This assumes that the second lag vessel now becomes the lead vessel. The other vessel will have the exhausted carbon regenerated or replaced and put back on-line as the lag vessel. The length of time that a carbon vessel should remain on-line is very site-specific. In this example, design the system for 3 months between carbon changes of the lead vessel. It is difficult to determine the exact amount of carbon needed. Below is a method of estimating the amount of carbon that is needed.

(a) *Calculate the Partial Pressure of Each Contaminant in the Air Phase.* Assume that the pressure in the carbon vessel is the same as the discharge pressure (12.7 psia). If this pressure is too different from the actual pressure, the partial pressure will need to be recalculated for the correct pressure in the carbon vessels.

$$\text{Partial pressure of PCE} = (\text{total system pressure}) \frac{\text{ppmv contaminant}}{10^6 \text{ ppmv air}}$$

$$\text{Partial pressure of PCE} = (15 \text{ ppmv}) (12.7 \text{ psia}) \cdot (10^{-6}) = 1.9 \times 10^{-4} \text{ psia}$$

$$\text{TCE} = (14 \text{ ppmv}) (12.7 \text{ psia}) \cdot (10^{-6}) = 1.8 \times 10^{-4} \text{ psia}$$

$$\text{Benzene} = (9 \text{ ppmv}) (12.7 \text{ psia}) \cdot (10^{-6}) = 1.1 \times 10^{-4} \text{ psia}$$

$$\text{Toluene} = (5 \text{ ppmv}) (12.7 \text{ psia}) \cdot (10^{-6}) = 0.63 \times 10^{-4} \text{ psia}$$

The weight of contaminant that can be adsorbed per weight of activated carbon can be estimated from isothermal data supplied by the carbon manufacturer or from the literature (see Paragraph 3-3a). From these data, the weight of contaminant adsorbed per weight of carbon was estimated from the Freundlich isotherm relationship:

$$\frac{x}{m} = KC^{\frac{1}{n}} \quad .$$

The values of  $K$  and  $1/n$  were obtained for one carbon type at 77°F. These values must be obtained for each type of carbon being evaluated and for each temperature (see Table B-2).

**Table B-2**  
**Fruendlich Isothermal Data**

| Contaminant | Temp | $K$ | $C$ (psia)           | $\frac{1}{n}$ | $\frac{X}{m}$ |
|-------------|------|-----|----------------------|---------------|---------------|
| PCE         | 77°F | 1.4 | $1.9 \times 10^{-4}$ | 0.156         | 0.368         |
| TCE         | 77°F | 1.4 | $1.8 \times 10^{-4}$ | 0.23          | 0.193         |
| Benzene     | 77°F | 1.1 | $1.1 \times 10^{-4}$ | 0.131         | 0.151         |
| Toluene     | 77°F | 0.7 | $6.3 \times 10^{-5}$ | 0.111         | 0.239         |

See Appendix C on generation of isotherms. See Section 2-3 for a discussion on  $K$  and  $1/n$ .

(b) *Determine the weight of each contaminant to be adsorbed per unit time.*

$$\frac{1 \text{ lb mole PCE}}{\text{min}} = n = \frac{PV}{RT}$$

$$\frac{1 \text{ lb mole PCE}}{\text{min}} = \frac{\left(1.9 \times 10^{-4} \text{ psia}\right) \left(2000 \frac{\text{ft}^3}{\text{min}}\right)}{\left(\frac{10.73 \text{ ft}^3 \text{ psia}}{\text{lb mole } ^\circ \text{R}}\right) (460 + 60^\circ \text{R})}$$

$$= 6.8 \times 10^{-5} \frac{\text{lb mole}}{\text{min}}$$

$$\begin{aligned} \frac{\text{lb PCE}}{\text{min}} &= \left( \frac{1 \text{ lb mole PCE}}{\text{min}} \right) (\text{molecular weight of PCE}) \\ &= \left( \frac{6.8 \times 10^{-5} \text{ lb mole}}{\text{min}} \right) (166) \frac{\text{lb}}{\text{lb mole}} \\ &= 1.1 \times 10^{-2} \frac{\text{lb PCE}}{\text{min}} \end{aligned}$$

$$\begin{aligned} \frac{\text{lb PCE}}{3 \text{ months}} &= \left( \frac{\text{lb PCE}}{\text{min}} \right) \left( \frac{1440 \text{ min}}{\text{day}} \right) \left( \frac{30 \text{ day}}{\text{mo}} \right) (3 \text{ months}) \\ &= \left( 1.1 \times 10^{-2} \right) (1440) (30) (3) \\ &= 1465 \text{ lb} \frac{\text{PCE}}{3 \text{ months}} \end{aligned}$$

$$\begin{aligned} \frac{\text{lb carbon}}{3 \text{ months}} &= \left( \frac{1465 \text{ of PCE}}{3 \text{ months}} \right) \left( \frac{\text{lb carbon}}{0.368 \text{ lb PCE}} \right) \\ &= 3981 \frac{\text{lb carbon}}{3 \text{ months}} \end{aligned}$$

$$\text{lb carbon for } \frac{\text{TCE}}{3 \text{ months}} = 5720 \text{ lb}$$

$$\text{lb carbon for } \frac{\text{Benzene}}{3 \text{ months}} = 2662 \text{ lb}$$

$$\text{lb carbon for } \frac{\text{Toluene}}{3 \text{ months}} = 1138 \text{ lb}$$

$$\text{Total lb carbon for 3 months} = (3981 + 5720 + 2662 + 1138) = 13501 \text{ lb}$$

This calculation is only an estimate of the quantity of carbon required. Manufacturers recommend calculating the carbon needed for the three or four most prevalent constituents and then adding a safety factor. Safety factors may be as little as 20% more carbon than calculated for non-regenerable systems to as high as 100% for a very conservative design. Applying a conservative safety factor of 100%, we see that the estimated carbon total ( $M$ ) becomes:

$$M = 13,501 \times 2 = (27,002) \text{ lb for 3 months}$$

(2) *Determine the Size of the Carbon Adsorption Vessels.*

(a) *Estimate the Diameter of the Carbon Vessel.* The designer often has the option, within limits, of using a large diameter vessel that is short, or a smaller diameter vessel that is tall. Both will hold the same amount of carbon. A third option is to use two vessels in parallel. As a starting point, calculate the diameter for a reasonable superficial velocity. Superficial velocity ( $V$ ) is the velocity that the vapor would attain through the carbon bed if this vessel were empty ( $V = Q/A$ , where  $Q$  is the vapor flow rate and  $A$  is the cross-sectional area of the vessel). Many carbons can be used over a large range of superficial velocities. Manufacturers' literature lists superficial velocities from 5 ft/min to several hundred. Typical superficial velocities are 10 to 100 ft/min. As superficial velocities increase, the pressure drop through the vessel increases. This results in increased energy costs. For this example, initially assume a superficial air velocity through the carbon vessels of 50 ft/min. Calculate the resulting diameter of the vessel as follows:

$$A = \frac{Q}{V}$$

$$A = \left[ \frac{3.14}{4} \right] \left[ D^2 \right]$$

Combining yields:

$$D = \left[ \frac{4 Q}{3.14 V} \right]^{0.5} = \left\{ \frac{4 (2000 \text{ cfm})}{(3.14) \left( 50 \frac{\text{ft}}{\text{min}} \right)} \right\}^{0.5} = 7.1 \text{ ft}$$

(b) *Estimate the Depth of the Carbon in the Vessels.*

$$M = [Vol] [\text{carbon density}]$$

$$Vol = \left[ \left( \frac{3.14}{4} \right) \right] [ (D^2) (H) ]$$

where

$Vol$  = volume of the carbon in the vessel

$M$  = weight of the carbon

$H$  = depth of the carbon in the vessel.

Combining, rearranging and estimating the carbon density to be 30 lb/ft<sup>3</sup> yields :

$$\begin{aligned} H &= \left[ \frac{(4) (M)}{(3.14) (D^2) (\text{carbon density})} \right] \\ &= \left[ \frac{(4) (27,002)}{(3.14) (7.1)^2 (30)} \right] \\ &= 23 \text{ ft} \end{aligned}$$

The carbon vessel is too deep. By decreasing the superficial velocity through the carbon bed from 50 to 25 ft/min and repeating the calculations done in Paragraphs B-2c(2)(a) and B-2c(2)(b) above, the diameter of the vessel becomes 10 ft and the carbon depth ( $H$ ) becomes 11 ft. These are acceptable (an alternative is to use four vessels,  $2 \times 2$ ). Vessels available from manufacturers will dictate their exact height and diameter.

(3) *Determine the Total Pressure Drops through the Units in the Process Train.* The actual pressure drops must be calculated for each application. They will most likely differ much from those chosen here to illustrate the calculation procedure.

(a) *Blower through Air Stripper, Valves, and Instruments.* 5 in. of H<sub>2</sub>O (estimate).

(b) *Air Stripper to Heat Exchanger Piping, Valves, and Instruments.* 1 in. of H<sub>2</sub>O (estimate).

(c) *Heat Exchanger.* 1 in. of H<sub>2</sub>O (estimate).

(d) *Heat Exchanger to Carbon Vessels Piping, Valves, and Instruments.* 1 in. of H<sub>2</sub>O (estimate).

(e) *Carbon Vessels.* The pressure drop through the carbon bed is a function of the type of carbon, the velocity of the vapor through the carbon bed, and the depth of the carbon bed. For one specific carbon in manufacturers' literature, the pressure drop through the carbon is 0.8 in. of H<sub>2</sub>O per foot of carbon bed. For the 11-ft bed of carbon in this example, the pressure drop is 9 in. of H<sub>2</sub>O for the lead vessels and 9 in. of H<sub>2</sub>O for the lag vessel, for a total of 18 in. of H<sub>2</sub>O (see Figure B-1).

(f) *Between Carbon Vessels:* 1 in. of H<sub>2</sub>O (estimate).

(g) *Carbon Vessels to Ambient Air Discharge Point:* 1 in. of H<sub>2</sub>O (estimate).

(4) *Determine the Size and Type of Blower.*

(a) *Size of Blower.* Design the blower to handle 2000 cfm for the above total system pressure drop. The exit pressure from the blower is the pressure leaving the carbon units (12.7 psia) plus the pressure drop through the treatment train. The blower exit pressure is as follows:

$$\begin{aligned}
 &= 12.7 \text{ psia} + (5 + 1 + 1 + 1 + 18 + 1 + 1) \text{ in. H}_2\text{O} \left( \frac{0.036 \text{ psia}}{(\text{in. H}_2\text{O})} \right) \\
 &= 12.7 + (28) (0.036) \\
 &= 13.8 \text{ psia}
 \end{aligned}$$

Blower performance curves must be obtained from the manufacturer. In the absence of this information, the design engineer can estimate the adiabatic (theoretical) horse power from thermodynamic relationships as follows. (See an engineering thermodynamics book for an additional discussion and development of these relationships.)

$$HP = \left( \frac{(P_1)(V_1)}{[33000]} \right) \times \left[ \frac{k}{(k-1)} \right] \left[ \left( \frac{P_2}{P_1} \right)^{\frac{k-1}{k}} - 1 \right]$$

HP = horsepower (hp)

$$P_1 = \text{inlet pressure in } \frac{\text{lb}}{\text{ft}^2} = \left( \frac{12.7 \text{ lb}}{\text{in.}^2} \right) \left( \frac{144 \text{ in.}}{\text{ft}^2} \right) = \left( \frac{1829 \text{ lb}}{\text{ft}^2} \right)$$

$$P_2 = \text{outlet pressure in lb / ft}^2 = \frac{13.8 \text{ lb}}{\text{in.}^2} = \frac{1987 \text{ lb}}{\text{ft}^2}$$

33000 = conversion factor

$$V_1 = \text{inlet volume} = \frac{2000 \text{ ft}^3}{\text{min}}$$

$C_p$  = heat capacity at constant pressure

$C_v$  = heat capacity at constant volume

$$k = \text{ratio of specific heats } \frac{C_p}{C_v} \quad (k = 1.4 \text{ air; } 1.31 \text{ methane; } 1.3 \text{ CO}_2)$$

Substituting yields:

$$\begin{aligned} HP &= (1829) \frac{(2000 \frac{\text{ft}^3}{\text{min}})}{33,000} \left[ \left( \frac{1.4}{1.4-1} \right) \right] \left\{ \left( \frac{1987}{1829} \right)^{\left[ \frac{(1.4-1)}{1.4} \right]} - 1 \right\} \\ &= 9.3 \text{ HP (at 100\% efficiency)} \end{aligned}$$

Prior to obtaining manufacturers data, a very rough estimate of the electrical motor size can be obtained by multiplying the adiabatic blower horse power (*HP*) by 40%. Using this number, we calculate the estimated size of the electric motor horse power is as follows:

$$\text{Electric motor } HP = \frac{9.3}{40\%} = 23 \text{ HP}$$

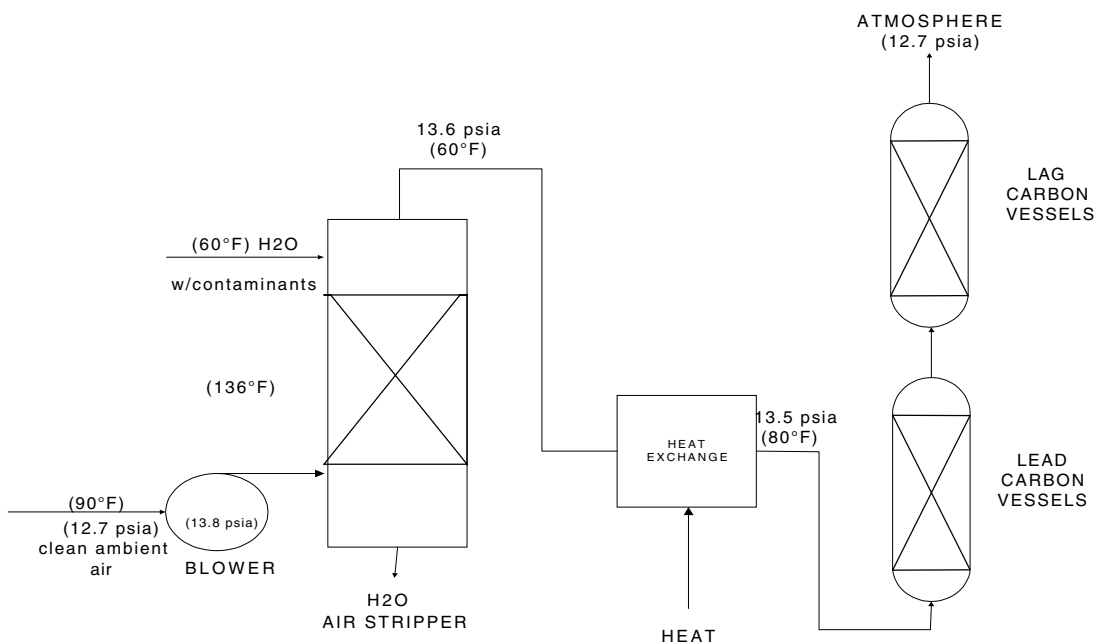
This value should not be used for final design; it should only be used if an initial estimate is needed. Manufacturer's data must be used for final design calculations.

(b) *Type of Blower.* High pressure centrifugal blowers are often used in this type of application.

(5) *Determine the Size and Type of Heat Exchanger.* The relative humidity (RH) of the

vapor stream entering the carbon vessels should not exceed 40 to 70% (see Paragraph 3-1b). A heat exchanger is used to raise the temperature (lower the RH) or lower the temperature (raise the RH) as needed. High RH reduces the adsorption capacity of the carbon. High temperature reduces the capacity of the carbon. A good compromise between temperature and humidity is to raise or lower the RH to about 50%. The type of heat exchanger depends on the amount of heating or cooling needed. Assume that in the air stripper the vapor stream is cooled to 60°F (the temperature of the water in the air stripper). Assume the vapor leaving the air stripper is saturated with moisture (100% relative humidity). A psychrometric chart tells us that the temperature must be raised in a heat exchanger from 60 to 80°F to lower the relative humidity to 50%.

- The Freundlich isothermal data listed in section 1a is for 77°F. In this example, this is close to the 80°F vapor temperature of the vapor entering the carbon units. If the temperature difference is large, the weight of contaminant adsorbed per weight of carbon ( $x/m$ ) must be determined for the new temperature and all subsequent calculations repeated.
- In addition to increasing the pressure, the blower also raises the temperature of a vapor stream. If the vapor goes directly from the blower to the carbon units, the temperature may need to be reduced, not raised, in a heat exchanger. It is difficult to estimate the temperature rise. The temperature rise must be obtained from manufacturers' blower literature.



**Figure B-2. Vapor phase activated carbon treatment train (English units).**